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NAWCAD Photogrammetrics: Methods and Applications for Aviation Test and Evaluation

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Abstract

Photogrammetrics, the science of extracting quantitative and qualitative data from multiple sequential recorded images, has been an integral part of flight test and evaluation at the Naval Air Warfare Center Aircraft Division (NAWCAD) at Patuxent River, MD for over 35 years. Photogrammetrics analysis is used for evaluation of stores separation, carrier suitability, range tracking, overhead impact scoring, and mishap reconstruction. The NAWCAD photogrammetrics team is pursuing strategies to reduce the time and increase the accuracies of solution processes that historically have been labor-intensive, prone to repetition of effort, and difficult to present. This paper describes how NAWCAD scientists have applied a clearly defined process for photogrammetrics efforts, and have implemented state-of-the-art hardware and software methodologies that reduce the turnaround time, increase the accuracy, and facilitate the delivery of custom formatted products to the flight test engineer's desktop.

Overview

Photogrammetrics is the science of extracting quantitative and qualitative data from multiple sequential recorded images. Derived from film and video, photogrammetrics data is analyzed to assist in determining the attitudes and position of objects (recorded in a two-dimensional image) in three-dimensional space. Photogrammetrics applications at the Naval Air Warfare Center Aircraft Division (NAWCAD) include:

- Carrier Suitability
- Stores Separation
- Range Tracking
- Overhead Impact
- Mishap Reconstruction

Photogrammetrics events require a great deal of flexibility in the design and application of solution algorithms. Photogrammetrics events occur in environments that can be hostile to a science rooted in precise measurements. In designing solution algorithms, photogrammetrics experts must take into account factors such as camera angle, camera movement, curvature of the earth, film quality, lens focal length and curvature, and environmental conditions. In the case of stores separation, cameras are attached to a moving aircraft and configured to capture the descent of a store or multiple stores attached to that aircraft. The photogrammetrics team has developed solution algorithms to accommodate a variety of conditions, including camera malfunction, camera movement, missing IRIG time on film, and other conditions which may affect the accuracy of the photogrammetrics solution.

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The NAWCAD photogrammetrics team has developed a photogrammetrics process consisting of seven phases:

1. Develop Test Plan
2. Mark and Survey
3. Camera Orientation
4. Mission
5. Film Processing
6. Data Reduction
7. Error Analysis, Answers, Graphics

The success of each phase of the photogrammetrics process is dependent upon the integrity of the preceding phase(s). For example, solution algorithms used during the *data reduction* phase rely on the accuracy of measurements obtained during the *mark and survey* phase. A wide variety of variables can affect the outcome of the photogrammetrics analysis. The photogrammetrics team has developed standard operating procedures for each phase of the photogrammetrics process. While individual projects often present unique challenges, the photogrammetrics team maintains the integrity of the photogrammetrics solution by approaching each project from a proven methodology platform. The photogrammetrics configuration must generate the flexibility to adapt to a wide range of conditions while adhering to an operating methodology that promotes a cohesive team-oriented strategy for obtaining accurate photogrammetrics solutions.

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Applications

Carrier Suitability & Range Tracking

Carrier suitability and store separation projects form the bulk of photogrammetrics work at NAWCAD. Carrier suitability events are flown on specific operational U.S. Navy aircraft carriers or at the Mark 7 arresting site and the TC-7 Catapult site at NAWCAD, Patuxent River, Maryland. Cameras are mounted at the site of the arrestment or take-off (see Figure 1).

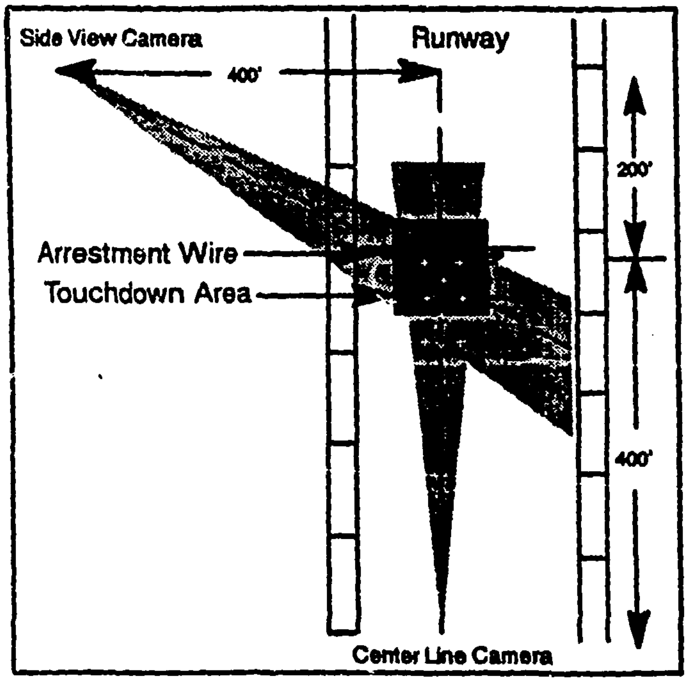


Figure 1. Mark-7 arresting gear camera configuration.

For carrier suitability applications, photogrammetrics analysis provides aircraft position and attitude information for catapult launches, touch-and-go's, and arrested landings (see Figure 2). The NAWCAD Photogrammetrics Team reduces data from tests performed at the NAWCAD arresting/catapult site, carrier certification trips, and other NAWCAD facilities.

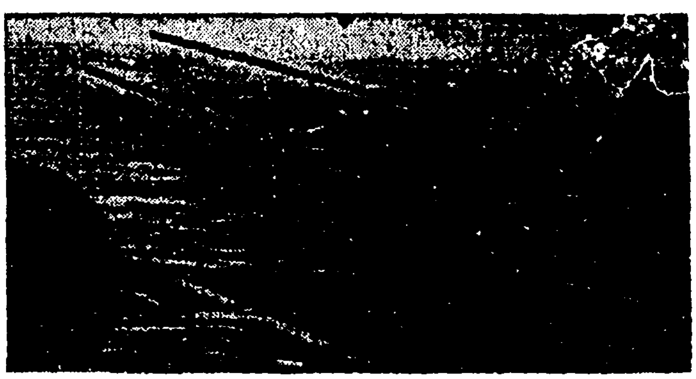


Figure 2. Carrier arrestment (photogrammetrics data points superimposed)

Stores Separation

Photogrammetrics analysis provides the position and orientation of a store with respect to the aircraft during store separation (see Figure 3). Velocities and rates are also provided using smoothing techniques. To record store separation events, cameras are mounted directly on the aircraft. In addition to camera angle, camera movement, and other factors indigenous to the photogrammetrics environment, the camera configuration must often overcome obstacles such as additional instrumentation, fuel tanks, vapor trails, and other stores which may block one or more camera views of a portion of the event.

Figure 3. Store separation event

As opposed to carrier suitability events where the cameras are mounted on a permanent *static* platform at the site of the event, store separation algorithms confront truth data that is obtained from cameras attached to the rapidly moving platform (the aircraft, see Figure 4), itself the primary subject of the photogrammetrics event. In addition, the cameras themselves are subject to movement relative to the store due to wing movement or fluctuation in air pressure/resistance.

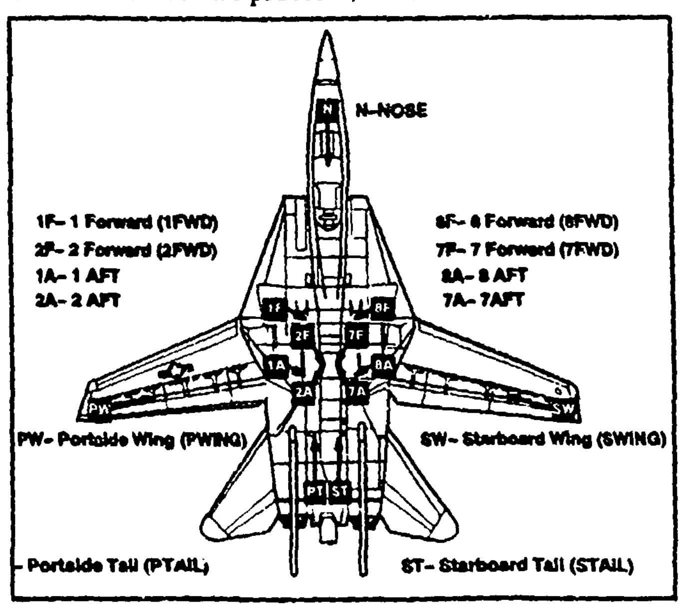


Figure 4. F-14D PDU camera configuration

To address the range of conditions that may be encountered during a stores separation event, the photogrammetrics team has developed several solution techniques. Solution methods include a *single camera* solution, *multicamera projection* solution, and *multicamera triangulation* solution. Each solution technique has inherent advantages and drawbacks. The *single camera* solution provides good position parallel to the film plane and reasonable attitude information, but depth perception is less accurate and the answers can be unstable. With the *multicamera* solutions, three or more cameras are used to quantify error. Four or more cameras are used to quantify relative errors. The *multicamera* solutions offer flexibility because the target can be located anywhere on the store. The *multicamera triangulation* solution is the most accurate solution currently available. When multiple cameras are used and triangulation can not be accomplished, the *multicamera projection* solution is applied. With *multicamera projection*, a target remains useful even if it is seen by only one camera. The predicted x,y,z of a target can be projected onto any film plane.

In addition to stores separation and carrier suitability, photogrammetrics analysis is used for overhead scoring, theodolite data processing, and mishap reconstruction.

Overhead Scoring

For overhead scoring applications, multiple store impacts near the Hooper Island target array are scored using film taken from the doorway of an observing helicopter. Boresight corrections are used to determine the azimuth and elevation of the impact splashes with respect to the camera.

Theodolite Data Processing

The Chesapeake Test Range (CTR) provides real-time (all digital) theodolite data processing. To significantly increase the accuracy of the results, photogrammetrics analysis methods are used to incorporate boresight corrections into the raw data. The photogrammetrics team typically provides positional tracking of aircraft. Photogrammetrics analysis methods are used to reduce and calculate data from weather balloons.

Mishap Reconstruction

For mishap reconstruction, photogrammetrics provides six-degrees-of-freedom (6-DOF) data (x,y,z, plus roll, pitch, and yaw positioning) from film and video. Since the film/video from such occurrences typically is not of the best quality or source (e.g. home video cameras), the task of accurately reducing this data is complex. Creativity and flexibility are required to extract useful results from these sources. The information collected is used for animation on a graphics workstation. Once the information is available on the workstation, different perspectives or viewing orientations are available.

The Process

The NAWCAD Photogrammetrics Team has developed and refined a clearly defined process for photogrammetrics analysis. In order to gain some insight into the relationship among all phases of the photogrammetrics process, the seven phases of the process (see Figure 5) will be explored from the perspective of a stores separation application.

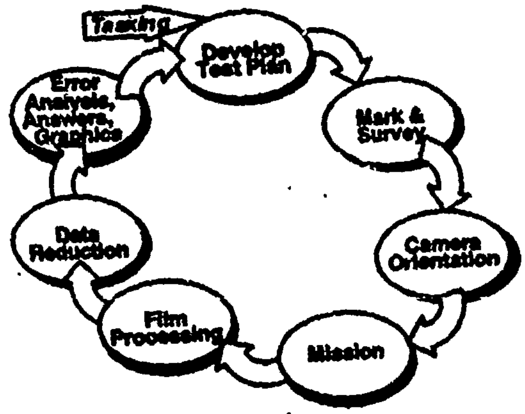


Figure 5. Photogrammetrics phases

Test Plan Development

The first phase in the photogrammetrics process involves developing the test plan. During this phase, the photogrammetrics team gathers information which will guide the entire photogrammetrics process.

The photogrammetrics team must ascertain such information as:

- The proposed number of flights per day
- The proposed number of events per flight
- The exact nature of each event (single or multiple release)
- Expected turnaround time for delivery of photogrammetrics data
- The number of cameras to be attached to the aircraft
- The number and size of the stores
- Any additional equipment which may be attached to the aircraft: specialized instrumentation packages, fuel tanks, etc.

- Any project-specific information

Of special interest to the photogrammetrics team is the design of the targets attached to or painted on the aircraft and store. Targets are placed on the aircraft and store to enable the photogrammetrics team to identify the attitude and position of a camera (relative to the store) or a released store. The shape and color of the target are critical to the accuracy of the photogrammetrics solution. If the target is clearly identifiable on film or video, the photogrammetrics team can produce accurate, timely photogrammetrics solutions. A poorly designed target will hamper the photogrammetrics process and can diminish the integrity of the photogrammetrics solution.

A well constructed test plan enables the photogrammetrics team to make the preparations necessary to obtain solutions on time and within budget. Certain project-specific conditions may require software modifications. Other test plan specifications may require upgrades to the existing hardware configuration. A strategic approach to the test planning phase will help to ensure the timely and accurate delivery of photogrammetrics data.

Aircraft and Stores Survey

After the test plan has been developed, the photogrammetrics survey team performs a *survey of the aircraft and stores*. Photogrammetrics solution algorithms rely on truth data obtained from the initial survey of the aircraft and stores; it is imperative that these measurements be accurate. Because survey tools and methods vary and because photogrammetrics-oriented surveys emphasize measurements that may have little significance in other applications, the NAWCAD photogrammetrics team employs its own aircraft and stores survey expert. By standardizing the tools and methods for aircraft and stores surveys, the potential for erroneous, incompatible, or incomplete survey measurements is significantly reduced. A meticulous, photogrammetrics-oriented survey provides a full range of measurements that can be applied to a variety of situations. Accurate and complete photogrammetrics survey measurements provide an increased range of options when problems are encountered during a photogrammetrics event or analysis.

Measurements obtained from the survey of aircraft and stores produce data that is crucial to photogrammetrics solutions. The survey provides the position of targets located on a store. In addition, the survey must provide the exact location of cameras attached to the aircraft, the distance from one camera to another, and the distance from a particular camera to the stowed position of the store. These measurements are essential to the accuracy of photogrammetrics solutions, such as triangulation.

Each type of photogrammetrics application, from carrier suitability to overhead impact, entails a different set of challenges and requirements for photogrammetrics-oriented surveys. Within each photogrammetrics application, project-specific requirements often produce unique conditions for photogrammetrics surveys. Regardless of the specific application, the photogrammetrics survey team must deliver accurate results and maintain the flexibility necessary to accommodate a variety of situations.

Camera Orientation

The third phase of the photogrammetrics process deals with *camera orientation*. During the test planning phase, the photogrammetrics customer details the flight test event and the portion of the event that should be captured for photogrammetrics analysis. The cameras are then configured to capture the specified range of the event. If critical portions of the event are not captured, additional flights may be required, resulting in unnecessary time delays and cost overruns.

Camera orientation is based on several factors:

1. View volume of each camera, which is dictated by the size and calibration of the lens, the type of film used, and the distance from the camera to the object being viewed.
2. Instrumentation of the camera or the number of frames captured per second.
3. Number of cameras used and the location of each camera (derived from the initial survey).
4. Data obtained during the test plan phase such as the release points and conditions for ejection of store.

Mission

The *mission* phase of the photogrammetrics process consists of the actual flight tests and is under the control of the photogrammetrics customer.

As is the case in every phase of the photogrammetrics process, communication between the photogrammetrics team and the photogrammetrics customer is vital. If any flight test parameters are changed during the mission, the photogrammetrics team must be informed. Difficulties experienced by the photogrammetrics data reduction team must be communicated immediately to the customer so that ongoing missions can be modified.

If, during the mission phase, the release points are changed, the cameras must be reoriented.

If the test plan has been adequately developed, the survey accurately performed, and the cameras properly oriented, then the mission should result in cost-effective, accurate solutions.

Film Processing

Film processing is performed by the NAWCAD Photo Lab. Once again, communication plays a key role. If a high volume of film is to be processed, the photo lab must be given enough lead time to prepare for increased processing. During the test plan development phase, an estimate should be given for film processing volume and expected turnaround time. If the project uses video instead of film, then the film processing phase is eliminated and the photogrammetrics team can immediately proceed to the data reduction phase.

Data Reduction

The sixth phase of the photogrammetrics process, *data reduction*, represents the most time-consuming, labor-intensive portion of the photogrammetrics process. Data reduction involves two steps: data extraction and solution calculation. Data extraction is performed using two primary systems: the *Telereadex* film reading machines and the *Semi-Automated Film/Video Reader* (SAFVR). Once extracted, the data is fed into one or more data reduction software packages. The data reduction software converts the data to the desired format, performs various photogrammetrics solution algorithms, and provides quality assurance verification.

Data Extraction

The bulk of data extraction work is performed on the Telereadex film reading machines. Data from film or video must be extracted and converted to a format that can be read by a variety of data reduction and software analysis packages. The Telereadex machines are a proven tool for obtaining photogrammetrics data from film.

Each film frame is encoded with numbers that correspond to specific events. After the film is loaded onto the Telereadex, the film is fast forwarded to the first frame in the first event to be read. Film reading experts align vertical and horizontal (x,y) cross hairs on specified points on the object to be analyzed. The cross hairs are linked to a numeric mapping system which records the x,y location of each point read. For store separation, the points read are portions of targets attached to the store and the aircraft. The number of points read are determined by the target design, the shape and size of the store, the visibility of the store and targets, and other event-specific factors.

The data extraction process is similar for the Semi-Automated Film/Video Reader (SAFVR) — except that once the system has been set up to read a specified event, the points are read automatically in an ideal scenario; experience with the SAFVR technology has been that manual intervention and reading assistance is often required. The SAFVR system reduces video as well as film. SAFVR is a one-of-a-kind system procured and developed specifically for photogrammetrics data reduction at NAWCAD.

The success or failure of the data extraction phase is linked to the integrity of the previous phases of the photogrammetrics process. The *survey* of the aircraft and store is performed using data from the *test plan*. The *camera orientation* is accomplished using data from the *test plan* as well as measurements obtained from the *survey*. If the communication process is maintained during the *mission* and *film processing* phases, then the required data will be captured on film and extracted for *data reduction* purposes.

Factors such as film quality, weather, mission time of day, and camera malfunctions can affect the data extraction process. The photogrammetrics team must maintain the flexibility to adjust to conditions beyond its control. As long as the integrity of the photogrammetrics process is not compromised, the photogrammetrics team can often successfully respond to unforeseen circumstances. If, for example, a particular camera breaks, the data reduction algorithm can be modified to account for missing data. If the remaining data is accurate, the photogrammetrics solution will not suffer a significant reduction in accuracy.

Data Reduction Solution Algorithms

The NAWCAD photogrammetrics team has developed photogrammetrics software packages to support a wide range of requirements. Our primary requirement is to ensure that the data is accurate. Once extracted from film or video, the data is run through one or more data validation software packages. After it has been validated, the data is run through a software package geared towards specific customer requirements.

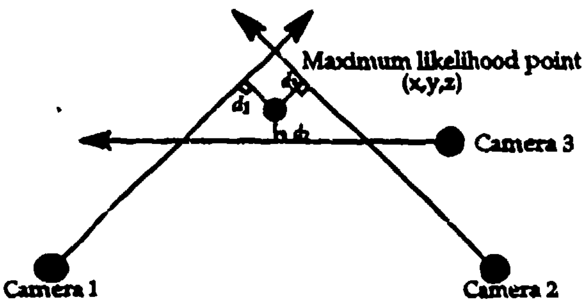
Typically, store separation flight testing consists of numerous flights that approach the edge of the separation envelope in small, incremental steps. Store separation analysis must define the separation envelope. The separation envelope encompasses the range of parameters that indicate that conditions are safe for ejection of the store. The edge of of the separation envelope is the final point at which a store can be safely ejected from an aircraft. The standard single-camera photogrammetrics solution is easy to use and provides reasonable results. However, the required number of flight test events make flight testing costs prohibitive.

To assist in reducing the amount of flight testing and increase the accuracy of the results, the NAWCAD photogrammetrics team developed the multicamera triangulation algorithm. Three or more cameras are used to quantify error. Four or more cameras are used to quantify relative error. To achieve a solution,

$$T(x, y, z) = \sum_{i=1}^{n} t_i , \; n \geq 2$$

is minimized by finding x,y, and z, satisfying:

$$\nabla T(x, y, z) = (0, 0, 0)$$



Multicamera triangulation enables photogrammetrics customers to approach the edge of the separation envelope with a greater degree of confidence.

When triangulation can't be accomplished, multicamera projection is applied. With multicamera projection, a target remains useful even if it is seen by only one camera. The predicted x,y,z of a target can be projected onto any film plane.

The photogrammetrics team has developed software packages for the full range of photogrammetrics applications from carrier suitability to mishap reconstruction.

Product Delivery

To complete the photogrammetrics process, the photogrammetrics team must deliver photogrammetrics solutions in the formats specified by the customer, when and where the customer needs them. Often, solutions are delivered in the form of graphs or tabular lists. To allow customers to perform additional analysis at their own desktops, photogrammetrics data is converted to generic formats that can be processed by most major software analysis packages.

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Robert Stancil is the photogrammetrics project coordinator for the Software and Engineering Applications Department (SEAD) of the Range Directorate (RD) at the Naval Air Warfare Center Aircraft Division (NAWCAD), Patuxent River, MD. A computer scientist for SEAD since 1989, Mr. Stancil's previous assignments have included the design and development of graphics software and numerous flight test data reduction programs for projects including the A-6E Rewing and various T-45, F-14, and F-18 programs. In March 1993, Mr. Stancil joined the Photogrammetrics group in SEAD, where he assisted in flight test analysis for the F-14 Pre-Deployment Update (PDU) project. In November '93, he was designated SEAD's single point-of-contact for organizing and coordinating film and video projects requiring photogrammetrics analysis from the Strike Aircraft Test Directorate, Rotary Wing Directorate, and Force Warfare Directorate at NAWCAD, Patuxent River, MD. Mr. Stancil was graduated in 1988 from St. Mary's College of Maryland with a Bachelor of Science degree in mathematics and computer science.

Mr. Alec E. (Ed) Forsman is the primary software developer for NAWCAD photogrammetrics applications. For the past seven years, as a computer scientist working for NAWCAD's Range Directorate, Mr. Forsman's efforts have involved many post-flight data reduction tasks concerning almost all types of U.S. Navy aircraft. He has developed many of the photogrammetric applications currently in use at NAWCAD. Mr Forsman coauthored the paper "Photogrammetric Methods on a Cold Weather Range," presented to the Range Commanders Council in 1990. Mr. Forsman is a graduate of the University of Chicago, where he received a bachelor's degree in mathematics in 1987.

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